ASDEX Upgrade LETTER
Max Planck Institute for Plasma Physics

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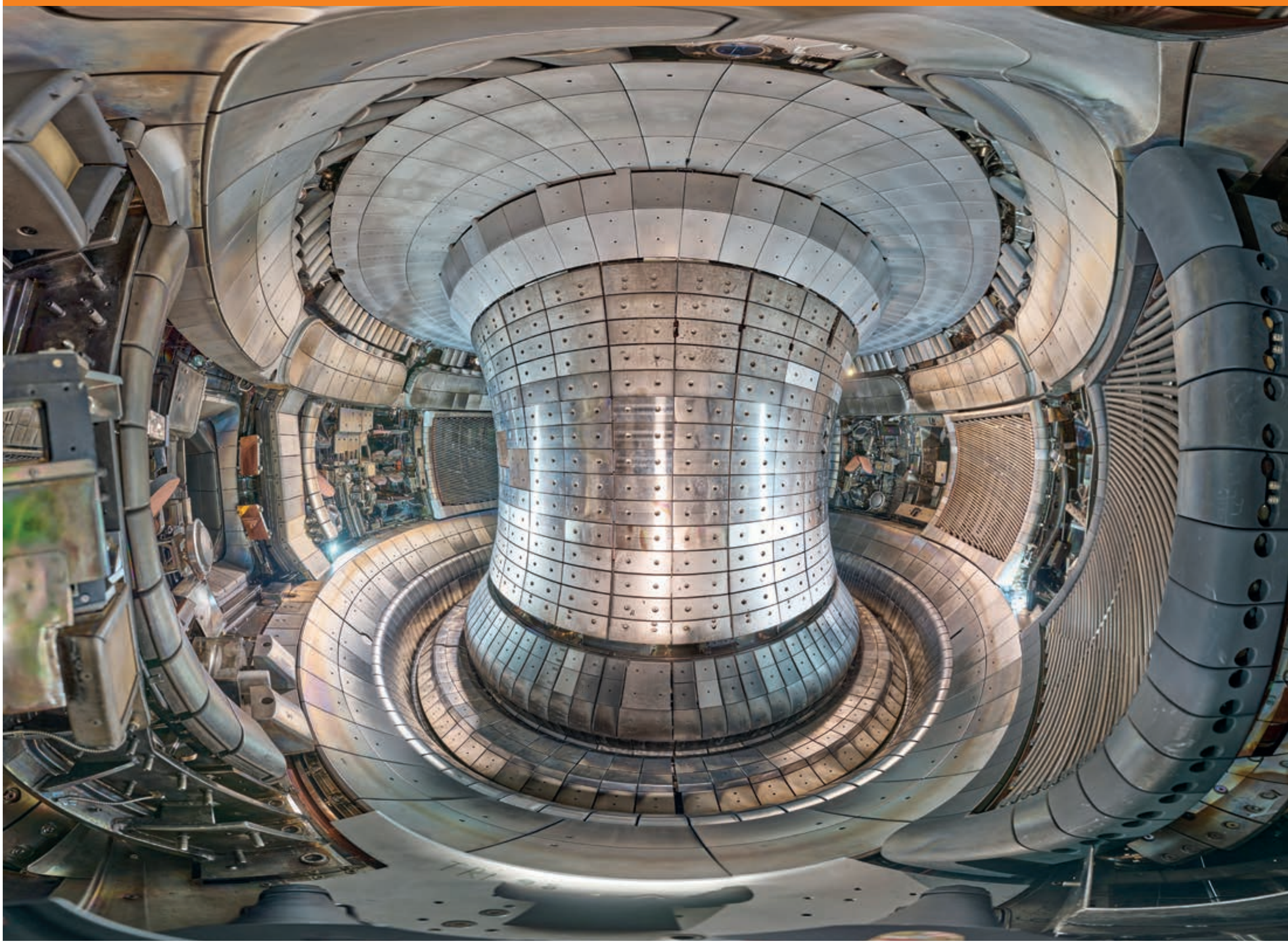
IN GARCHING FOR EUROPE – FUSION RESEARCH WITH THE ASDEX UPGRADE TOKAMAK



Fish-eye view into the interior of the ASDEX Upgrade vacuum vessel in August 2024, following the installation of the new upper divertor (photo: V. Rohde).

Irene Zammuto, Head of the AUSBAU Group (Photo: MPI for Plasma Physics)

Editorial

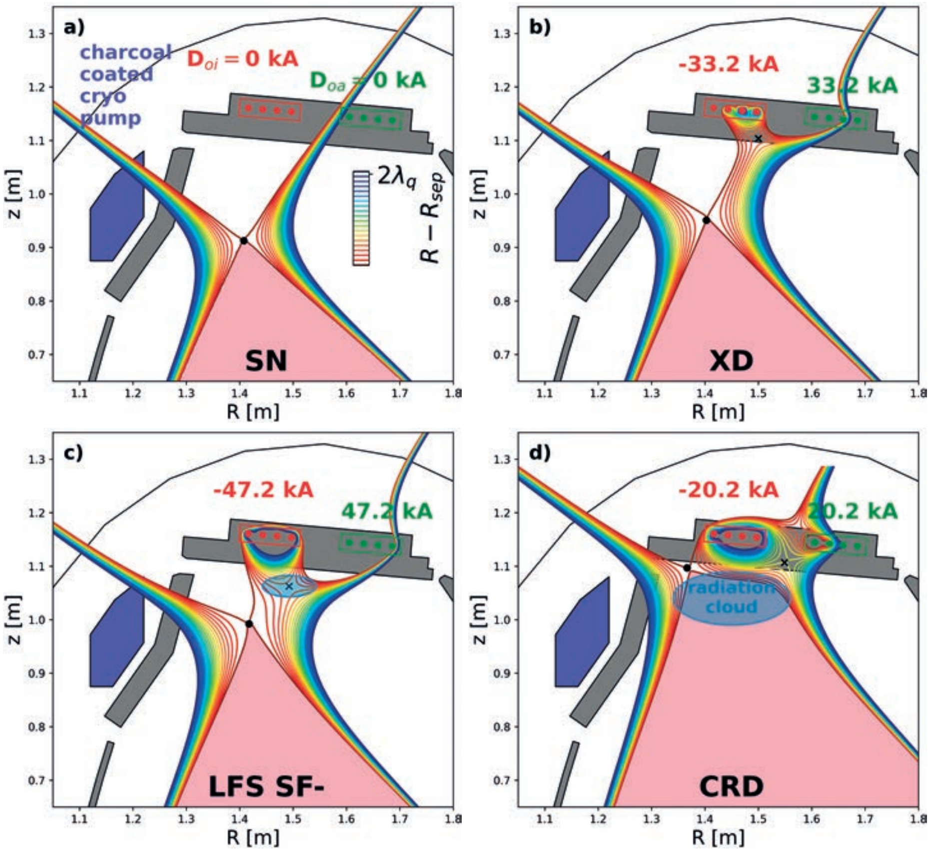
After a two-year maintenance period, ASDEX Upgrade resumed operations in November 2024. This upgrade phase introduced significant changes to enhance operational flexibility, particularly in divertor configurations and exhaust handling. A key enhancement was the installation of a new upper divertor, enabling alternative magnetic configurations and improved plasma exhaust management. Since August 2022, ASDEX Upgrade has undergone maintenance to install components like a helium-extracting cryopump, inner and outer divertor modules, and two concentric coils capable of producing a variety of alternative divertor geometries. A newly designed flat divertor was also added for bi-directional magnetic helicity, supporting novel operational regimes. The reassembly of ASDEX Upgrade was completed on time in autumn 2024, and the electrical connection of the new coils has become operational in spring 2025. With the coils' activation, the studies of alternative divertor configurations is starting now, an overview of which is given in this special edition. We also describe the upper divertor components, and outline their installation strategy.

Finding the optimum exhaust solution for a fusion reactor

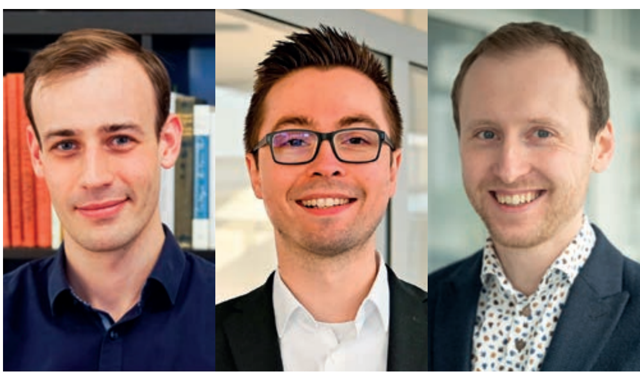
One of the outstanding challenges on the way to a fusion reactor is the exhaust of both the power as well as the particles produced by the fusion reactions. The component designed for this purpose in a tokamak like ASDEX Upgrade is called divertor and is conventionally operated in single-null (SN) configuration (upper left part of the figure). In order to study alternative divertor configurations systematically and find the best concept, ASDEX Upgrade has been installing a pair of in-vessel coils Doi and Doa (shown in red and green), new divertor targets (grey) and a new cryo-pump (dark blue) during the last opening lasting two years. These components will allow to study a variety of alternative divertor geometries, illustrated in the figure:

The goal of the X-divertor (XD) is to widen the strike line, i.e. to spread the power-carrying magnetic flux surfaces (rainbow-colored contour lines) at the target over a larger surface and thereby reduce the local heat load geometrically. This effect might be limited by the shallow field line angles at the surface and therefore the low-field side snowflake minus (LFS SF-) configuration might be the better choice. Here the goal is to stabilize a radiation cloud (blue ellipse) at a secondary X-point (black cross) and dissipate the thermal power of the plasma before it reaches the target surface. The large currents in the coils required to achieve such a configuration indicate that the realization might be challenging and/or expensive in a reactor and therefore a Compact Radiative Divertor (CRD) might be the best option. Here the radiating zone is allowed to penetrate the confinement region (faint red area) cooling the entire edge layer of the plasma. In ASDEX Upgrade the in-vessel coils are only needed to mimic the situation in a much bigger reactor that would not require such coils. The challenge of this configuration is to stabilize the radiation without polluting and diluting the confined plasma by impurities and thereby reducing the performance of the reactor, but recent experiments showed encouraging results.

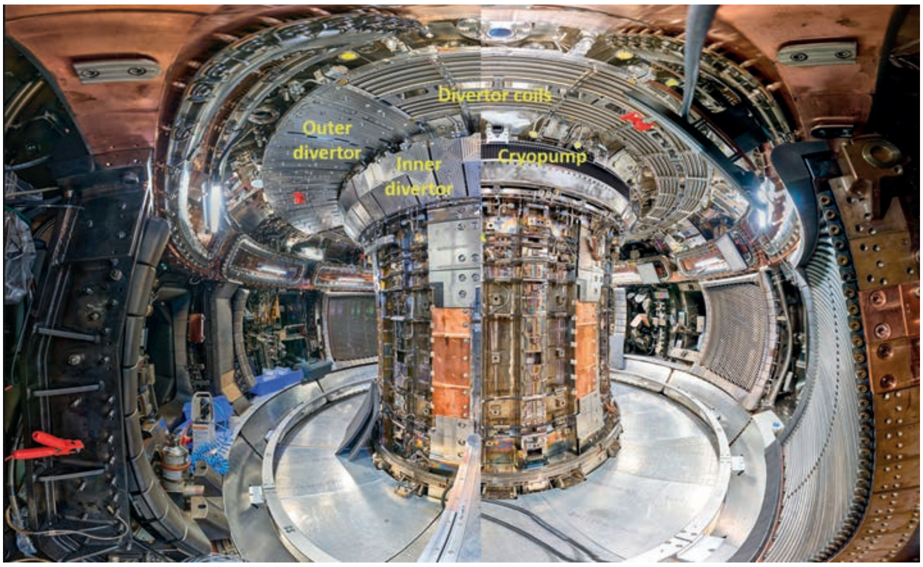
An important feature for all configurations is a special charcoal-coating on the cryo-pump developed for ITER to remove the 'Helium-ash' produced by the fusion reactions. At ASDEX Upgrade this is tested for the first time in a realistic Tokamak environment. *T. Lunt*



Conventional (SN) and alternative (XD, LFS SF-, CRD) divertor configurations in the new upper divertor of ASDEX Upgrade (figure: T. Lunt)



The new upper divertor with in-vessel coils



Main components of the upper divertor installed (picture: V. Rohde).

ASDEX Upgrade operates with strike lines in the upper or lower divertor, or both in a double-null configuration. Traditionally, the focus has been on ITER-like lower divertor configurations, but expanding the heat flux distribution required in-vessel coils near the strike line. To preserve existing features, the upgrade was implemented in the upper divertor. The new divertor consists of:

- Divertor Coils designed avoiding electrical joints, using a single 45 m conductor bent into shape without electrical joints. Thanks to an oblique port, the coil turns were bent horizontally and inserted into the vessel. The copper conductor (8 mm inner diameter, 18 mm outer) is encased in stainless steel and insulated with a 2.5 mm Tefzel HT 2183 layer. Each coil has four turns, carries a peak current of 13 kA for 4 s, limiting the heating to $\Delta T = 60$ K. Operational voltage reaches 300 V, rising to 5 kV during disruptions. Opposing current directions reduce the induced voltage, and an intelligent crowbar mitigates overvoltage effects. Coil terminations are sealed with CF35 flanges and bellows.
- A new cryopump behind the upper divertor controls the density, with a 50 m^3/s pumping speed and a 30 mm slit between the inner and outer divertor ensuring 20 m^3/s effective speed for hydrogen isotopes. The cryopump consists of 7 toroidally arranged modules, with two designs to allow direct plasma view for diagnostics. A 3-pass valve allows to adjust the pumping speed, and active charcoal enables 10 m^3/s helium pumping, using ITER-developed coating technology. A common cryo-supply serves both upper and lower cryopumps, with a connection box near the torus for separation.
- The inner divertor has 16 stainless-steel modules, each cooled by brazed stainless-steel tubes and attached to the vacuum vessel with supports that are only partially electrically insulated to optimize halo current path. Plates are toroidally connected for rigidity, but insulated.
- The outer divertor also has 16 modules, connected by electrically insulated flanges for water cooling to manage radial moments during disruptions. The cooling plate, supporting tungsten-coated graphite tiles (tungsten thickness: 10 µm), follows the same design as the inner divertor. The outer divertor is also the casing of the coils.
- The upper divertor targets face space constraints for fixings and are integrated into a toroidally stiff coil support. Toroidal target gaps of 1 mm with ±0.2 mm height difference were factored into design optimizations to minimize leading edge effects. The configuration allows operation with both field line helices, enhancing operational flexibility over the traditional 'fish-scale' design used in the lower divertor. 2D FEM thermal simulations determined an optimal chamfering, avoiding overheating. A new clamping solution allows fixing from the plasma side, with high-heat-load targets secured laterally via eccentric tappets and neighboring tiles fixed with front-side screws.

A. Herrmann

Award-winning dissertations: EPS PhD Award for Benedikt Zimmermann and Otto Hahn Medal for Jonas Puchmayr and Philipp Ulbl.
Benedikt Zimmermann's (left picture) dissertation at ASDEX Upgrade led to major progress in predicting plasma rotation in tokamaks. He showed that models can describe momentum transport in the plasma core, enabling the first measurements of key coefficients – laying groundwork for future fusion reactors. Jonas Puchmayr (middle picture) uses MHD simulations to study how 3D magnetic perturbation fields affect edge-localized modes (ELMs) in tokamaks. He extended the CASTOR3D code and showed where and why instabilities occur – revealing that while ELMs can be controlled, edge pressure is also reduced. Philipp Ulbl (right picture) enhances in his dissertation the GENE-X code with a collision model for improved edge-plasma simulations, successfully validating it against TCV-Tokamak experiments. Congratulations to the prize winners on this outstanding achievement!

Konrad Krug

Qualification of components and installation procedure

To achieve the required tolerances for installing the components in the vessel, the metrology team closely oversaw the entire installation process, meticulously monitoring each assembly phase to ensure compliance with strict specifications. The project progressed through the following key milestones:

- Conductor Design and Qualification – Tests determined minimum bending radius, maximum voltage, and insulation durability under ASDEX Upgrade conditions.
- ASDEX Upgrade mechanical twin development – Due to the complexity of installing the coils inside the vacuum vessel, an ASDEX Upgrade mechanical twin was developed to test and refine bending tools and procedures while also training the team. Three coils were bent, with two undergoing electrical tests at nominal current for about 1200 shots, simulating a full ASDEX Upgrade experimental campaign focused on the upper divertor.
- Implementation in ASDEX Upgrade – the installation of the divertor in ASDEX Upgrade guided by the insights gained during months of rigorous testing and prototyping.

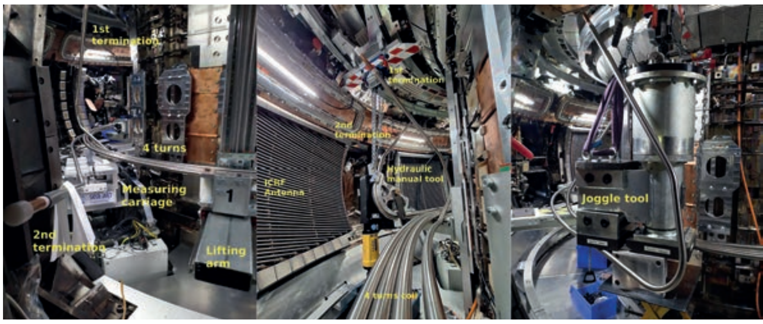
Coil Winding

A complex bending sequence was developed, alternating the automatic turn-bending system with manual hydraulic tools for shaping the terminations. Personnel of the Max Planck Institute for Plasma Physics in collaboration with Sea Alp developed specialized winding tools, handled complex bending.

View of the AUG Hall during the winding inside the vessel (picture: MPI for Plasma Physics).

Space constraints required some terminations to be pre-bent before vessel entry. Special tools and jigs were designed to ensure the bending process inside the vacuum vessel with the required precision in the range of tenths of a millimeter. The winding-line consists of:

- Unspooler & Straightener – Prepares conductor to access the vessel.
- Bending Machine – placed inside the vacuum vessel to bend the conductor, with its weight of 1.3 tons, it had to be assembled inside the vessel, as its access was limited by the diagonal of the port.
- Measuring Carriage & Marking System – Tracks conductor length to ensure the precision required.
- A pulling and lifting system to keep the bending machine force free and to place the conductor into the casing.



View of the AUG Vessel during the winding inside the vessel (picture: MPI for Plasma Physics).

The bended conductor is accessing a midplane port: the winding progressed inside-out, with a synchronized lifting system for coil insertion. Portable bending machines were used for terminations, ensuring precision with manual templates.

Despite the bending procedure qualified in the mechanical twin, challenges inside the ASDEX Upgrade vacuum vessel included:

- Tighter spatial constraints than expected.
- Restricted ASDEX Upgrade vacuum vessel room for handling tools.
- Nonlinear mechanical behavior of different conductor spools. The team's adaptability proved crucial in overcoming these obstacles.

Cryopump Installation

The cryopump, positioned between the vacuum vessel and inner divertor, required:

- Avoiding thermal contact with diagnostic cables.
- Maintaining electrical clearance to prevent arcing, as cryopumps are grounded to sector 13 and connected to LN2/LHe supply lines.

Plasma-Facing Components Implementation

Throughout the entire assembly process of the 384 tungsten-coated graphite tiles, laser scanner measurements were employed to ensure that vertical displacements were limited to just a few tenths of millimeters. After the initial assembly, only 5 % of the tiles do not meet the requirements, primarily involving tiles that incorporate diagnostics such as Langmuir probes and shunts. These tiles were dismounted and reinstalled with minor adjustments to meet the required tolerance.

I. Zammuto

Imprint

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